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Options for integrated beam experiments for inertial fusion energy and high-energy density physics research ☆

M.A. Leitner[a,*], C.M. Celata[a], E.P. Lee[a], B.G. Logan[a], W.L. Waldron[a], S.S. Yu[a], J.J. Barnard[b]

[a] *Lawrence Berkeley National Laboratory (LBNL), 1 Cyclotron Road, Bldg 47 R0112, Berkeley, CA 94720-8201, USA*
[b] *Lawrence Livermore National Laboratory (LLNL), 7000 East Avenue, Livermore, CA 94550, USA*

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Abstract

The Heavy Ion Fusion Virtual National Laboratory (HIF–VNL), a collaboration among LBNL, LLNL, and PPPL, is presently focused on separate smaller-scale scientific experiments addressing key issues of future Inertial Fusion Energy (IFE) and High-Energy-Density-Physics (HEDP) drivers: the injection, transport, and focusing of intense heavy ion beams at currents from 25 to 600 mA.

As a next major step in the HIF–VNL program, we aim for a fully integrated beam physics experiment, which allows integrated source-to-target physics research with a high-current heavy ion beam of IFE-relevant brightness with the goal of optimizing target focusing. This paper describes two rather different options for such an integrated experiment, the Integrated Beam Experiment (IBX) and the Neutralized Drift Compression Experiment (NDCX). Both proposals put emphasis on the unique capability for integrated injection, acceleration, compression, and focusing of a high-current, space-charge-dominated heavy ion beam.

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1. Introduction

The Heavy Ion Fusion Virtual National Laboratory (HIF–VNL) is currently completing [1] a set of three independent experiments, which are medium to driver scale in beam current and address scientific key questions related to subcomponents of an Inertial Fusion Energy (IFE) heavy-ion driver, namely the injector, the high-current quadrupole transport sec-

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*Corresponding author. Tel.: 510 486 4090; fax: 510 486 5392.
E-mail address: MLeitner@lbl.gov (M.A. Leitner).

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tion, and the final focus system. But for the scientific understanding of how the beam distribution evolves as it is passing sequentially through each region of a heavy-ion fusion driver, an integrated beam experiment is required as a next step.

Therefore, the HIF–VNL proposes a fully integrated beam physics experiment. It will allow integrated source-to-target physics research with a high-current heavy ion beam of IFE-relevant brightness with the goal of optimizing target focusing. This paper describes two different options for such an integrated experiment, the Integrated Beam Experiment (IBX) and the Neutralized Drift Compression Experiment (NDCX). As described further below, the IBX proposal mimics the historically evolved induction linac driver configuration [2] using quadrupole transport magnets. IBX focuses on the scientific exploration of ion beam evolution over a large number of transport lattice periods. IBX can be built with current state of the art technology.

On the other hand, the much smaller NDCX proposal puts more emphasise on beam compression physics and requires novel beam manipulation techniques currently under development. NDCX would push beam compression to the limits, therefore providing significant beam pulse energy on target ($10^{11}\,\mathrm{J/m^3}$) even for near-term high-energy-density experiments.

Since the transported beam intensities in NDCX are much higher than those in the IBX, NDCX will utilize solenoid transport magnets. As described in Ref. [3], solenoids have the capability to transport higher current densities than quadrupoles in the low-energy regime. The development of a single solenoidal channel transporting a high line charge density could lead to new, more attractive driver architectures [4] for heavy-ion fusion.

2. IBX

2.1. IBX goals

The main goals to be achieved by IBX can be divided into four broad areas [5]:

1. integrated beam physics,
2. longitudinal beam physics,
3. transverse/longitudinal coupling physics, and
4. transverse beam physics.

(1) Integrated beam physics includes a demonstration of injection, acceleration, compression, and focusing of a heavy-ion beam at line charge density similar to the initial stages of a driver. In particular, the physics involving interactions of beam ions with walls, residual gas, and stray electrons may be assessed. In parallel, simulations of a 3D beam from source-to-target, predicting final spot radius and current profile on target, would demonstrate an integrated theoretical understanding.

(2) Longitudinal physics includes the physics of drift compression and stagnation. Stagnation can be described as the process which utilizes the longitudinal electric field of the beam's space charge to remove the velocity tilt at precisely the final focus point and hence minimizes chromatic aberrations of the spot. Demonstration of stagnation is a major goal of IBX. Therefore, measurement of the velocity tilt and velocity spread remaining after beam compression by a factor of 10 will be a key goal of IBX. Further, the investigation of longitudinal heating during acceleration and subsequent compression will be of importance as well as investigations of longitudinal space-charge wave production and propagation.

(3) The third area to be explored is the physics of transverse–longitudinal beam phase-space coupling. The large velocity tilt required to compress the beam also manifests itself in the transverse dynamics, and so a number of topics related to coupling will be examined: matching and beam control with velocity tilt and acceleration; time-dependent final-focus correction physics; the transverse/longitudinal temperature anisotropy instability; bunched beam "end" physics, and beam halo production.

(4) Further, with the addition of acceleration and longitudinal compression, the currently performed drifting-beam fill-factor studies on the HIF–VNL High Current Experiment (HCX) will need to be revisited.

For more detailed descriptions of the IBX physics program see Refs. [5,6].

2.2. IBX specifications

For simplicity and cost savings, IBX will be a single-beam experiment (in contrast to a multiple, parallel beam accelerator for a HIF driver). Because of significant experiences with a 1.7 MeV injector and potassium ion sources, the IBX injector will provide ion species of singly charged potassium (atomic mass 39) at an injection energy of 1.7 MeV. The main IBX parameter ranges can be derived as follows:

- A beam current at 1.7 MeV of 0.2–0.7 A is necessary to reach a driver-relevant beam space-charge potential for meaningful integrated studies of electron effects and neutralized focusing.
- This establishes a requirement on the final IBX beam energy: At least 5–10 MeV are needed to have a low enough, but still aggressive, final perveance (measure of the ratio of space-charge potential energy to kinetic energy) of 10^{-4}–10^{-3} in order to be able to focus the beam to the final focus spot.
- In addition, a beam energy of 5–10 MeV will provide a sufficient number of transport half-lattice periods (50–100) for investigating transverse and longitudinal beam physics phenomena.
- An initial beam pulse length of 0.2–1 μs together with 5 Hz burst rate capability will allow operation at sufficient duty factor to investigate beam–wall and beam–vacuum interactions. Such a pulse duration and repetition rate will allow studying effects of gas on subsequent beam pulses, but the pulse duration is insufficient for gas desorbed by the beam head to affect the beam tail. By taking advantage of the IBX constant lattice-length design, a long pulse injector upgrade could allow studying such head-to-tail gas effects by having a long beam pulse coast along the IBX accelerator (without significant acceleration or compression).
- In order to provide a vacuum environment similar to a HIF driver, it is desirable to have at least a few superconducting transport magnets with a cold bore in IBX enabling dynamic vacuum experiments.
- In addition, to allow the experimental flexibility to conduct a range of different longitudinal beam physics experiments using varying acceleration waveforms, it is desirable to incorporate agile waveform control (i.e. induction cores with reconfigurable lumped element-pulsers and programmable solid-state amplifiers) into IBX.

The present IBX concept is schematically shown in Fig. 1. A single-beam heavy-ion induction linac using magnetic quadrupole transport magnets would accelerate ions of K^+ to 5 MeV (preferably to 10 MeV depending on funding level), then longitudinally compress the beam by a factor of up to 10 in the "drift compression" section. A final focusing section, including beam neutralization experiments, would follow the drift compression. A bend, which would be required in a future HIF driver in order to hit the target from two sides, could be added as an upgrade at a later stage. The final charge-per-unit-length will be 0.7 μC/m for the 5 MeV IBX case (1.4 μC/m for 10 MeV) in order to produce the space charge potential necessary for electron dynamics and final transport neutralization studies. The final perveance of the beam after longitudinal compression of a factor of 10 will be $\sim 10^{-3}$. The option of such aggressive beam compression will enable exploration of a wide range of final focus transport and final compression alternatives. The beam pulse length in the accelerator is only 200 ns in order to minimize core material in the induction accelerator cells. Fig. 2 shows a mechanical layout of a 10 MeV IBX case together with a magnetic bend integrated into the drift compression section. Fig. 3 shows a proposed IBX site in the HIF–VNL experimental facility at LBNL demonstrating the medium-scale size of the IBX project. To advance the integrated heavy-ion beam physics program in a time- and cost-effective manner IBX will rely mainly on the use of existing technology, in particular, induction core and superconducting quadrupole magnet designs developed in the HIF program. (See Refs. [7,8] for technical references on magnet and induction core technologies for IBX.)

2.3. IBX cost & schedule

The total IBX project cost including R&D and 30% contingency is currently expected to be in the

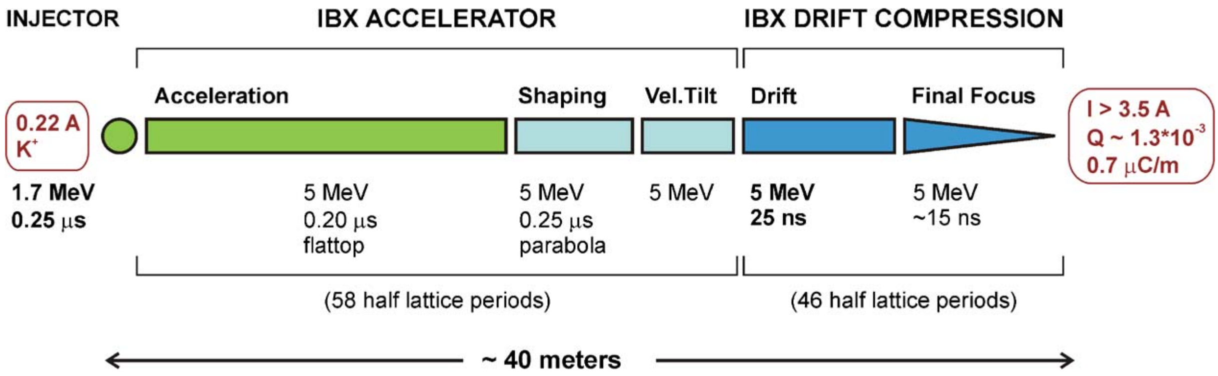

Fig. 1. Schematic concept of a 5 MeV integrated beam experiment (IBX).

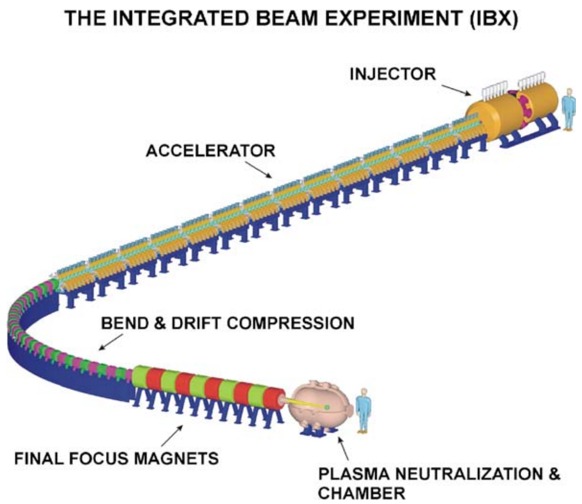

Fig. 2. Mechanical layout of a 10 MeV IBX case together with a magnetic bend integrated into the drift compression section.

range of 75 FY04-M$. Following project approval and a one-year conceptual design effort, IBX's first operation could begin after a 5-year design and construction schedule.

3. NDCX

3.1. NDCX goals

The most recent, and highly innovative, proposal for a much smaller integrated beam experiment is the Neutralized Drift Compression Experiment (NDCX). Contrary to IBX, which emphasizes the investigation of beam transport physics over a long transport lattice using existing technology, NDCX will develop novel, still unexplored beam manipulation techniques in order to establish the physics limits on compression of heavy-ion beams for creating high energy density matter and fusion ignition conditions. Contrary to IBX, which mimics a HIF fusion driver, NDCX is motivated by HEDP and integrates minimum capabilities to explore the applicability of heavy ions to HEDP.

Heavy-ion beams are an excellent candidate for high-energy-density physics studies by uniformly heating thin target plasmas with the Bragg peak located near the target center. By isochorically and uniformly heating material near solid densities to >1 eV ranges, a HEDP facility based on heavy-ion beams may enable a leap in the precision of warm dense matter and high-energy-density-physics studies [9,10]. The primary challenge in exploiting this desirable property is to compress the beam in time to short pulse lengths compared to the target disassembly time, while also compressing the beam radially to small focal spot size for high local deposition energy density.

In contrast to IBX, the NDCX would compress the beam within a neutralizing plasma, therefore significantly extending the transportable beam current into high-intensity regimes not reachable in the absence of background plasma. Plasma electrons can be used to neutralize much of the repulsive space charge that resists the beam compression in time and space, but the transverse

Fig. 3. Proposed IBX site in the existing HIF–VNL experimental facility at LBNL demonstrating the medium-scale size of the IBX project.

and longitudinal effective ion beam temperature ultimately limits the smallest achievable spot size and pulse duration after the space charge forces are removed from the beam inside plasmas. To minimize the beam temperature, and thereby maximize the energy deposition in the target, the beam dynamics must be controlled with high precision throughout the accelerator, using accurately positioned and tuned transport magnets, accelerating fields with precise timing and voltage regulation, and final charge neutralization techniques that do not degrade the beam quality.

A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy-ion beams, and a determination of how best to create, accelerate, transport, compress, and focus these beams to a small spot size are critical to achieve the scientific objectives of heavy-ion fusion and ion-beam-driven studies of warm dense matter. NDCX will allow experimental determination of the limits of heavy-ion beam compression in an integrated manner by studying the accumulated effects experienced by the beam as it travels from the source through the accelerator, and through longitudinal compression and finally focuses onto the target. As a major advance for the HIF–VNL, it could also provide significant beam pulse energy on target ($10^{11}\,\mathrm{J/m^3}$).

3.2. NDCX specifications

For heavy-ion beams with energies just above the Bragg peak in dE/dx (ion energy loss per unit range), possible target parameters to begin studying strongly-coupled plasma properties in the warm dense matter regime are few microns to tens of microns thick foils, ~1 J (single) beam energy, 0.2–2 ns final pulse duration, and 0.5–2 mm diameter focal spot sizes.

Exact specifications for NDCX are still in development, but Fig. 4 shows schematically a possible experimental layout together with a few proposed parameters. A novel injector scheme, the so-called ‘‘load-and-fire’’ injector, provides a high line charge density beam from a He^+ plasma ion source at +30 kV electric potential. A 1 A, 1 μs beam pulse is extracted through a −300 kV pulsed extractor electrode and subsequently decelerated to ground potential. In order to avoid immediate beam blow up, the beam has to be injected into a strong solenoid field (~3 T). An electrostatic lens system (not shown in Fig. 4) matches the beam into the solenoid close to Brillouin flow conditions. Because of the strong deceleration, the beam bunch almost stalls (at 30 keV energy) inside the solenoid and compresses longitudinally in space, increasing the line charge density by a factor of $\sqrt{10}$. The 30 keV, 1 μs beam pulse is ~1.2 m long, requiring a 2 m long solenoid.

After "loading" the beam into the solenoid, a +200 kV "fire" pulse is applied along a graded insulating column inside the solenoid, accelerating the beam out of the solenoid at constant line charge density. The graded insulator column (+200 kV at injection, ground at ejection) applies an approximately triangular voltage pulse leading to an energy tilt on the ion beam for further longitudinal beam compression through the subsequent accelerator section. Because of the high space charge, a strong solenoid (~3 T) transport system has to immediately follow the load-and-fire injector.

Several induction cells accelerate the beam and apply a significant tilt voltage for a 10 times bunch compression in the short accelerator section. At the end of the accelerator section, a fast induction cell with agile waveform control using solid-state pulser technology will serve as tilt corrector in order to adjust for tilt and acceleration errors. The beam parameters at the end of the accelerator are 10 A current and 100 ns bunch length. Because of the strong tilt voltage applied throughout the accelerating section, the beam energy is ramped from 500 keV at the bunch front to 1000 keV at the bunch end. The average beam energy is 750 keV, resulting in 0.75 J total beam energy.

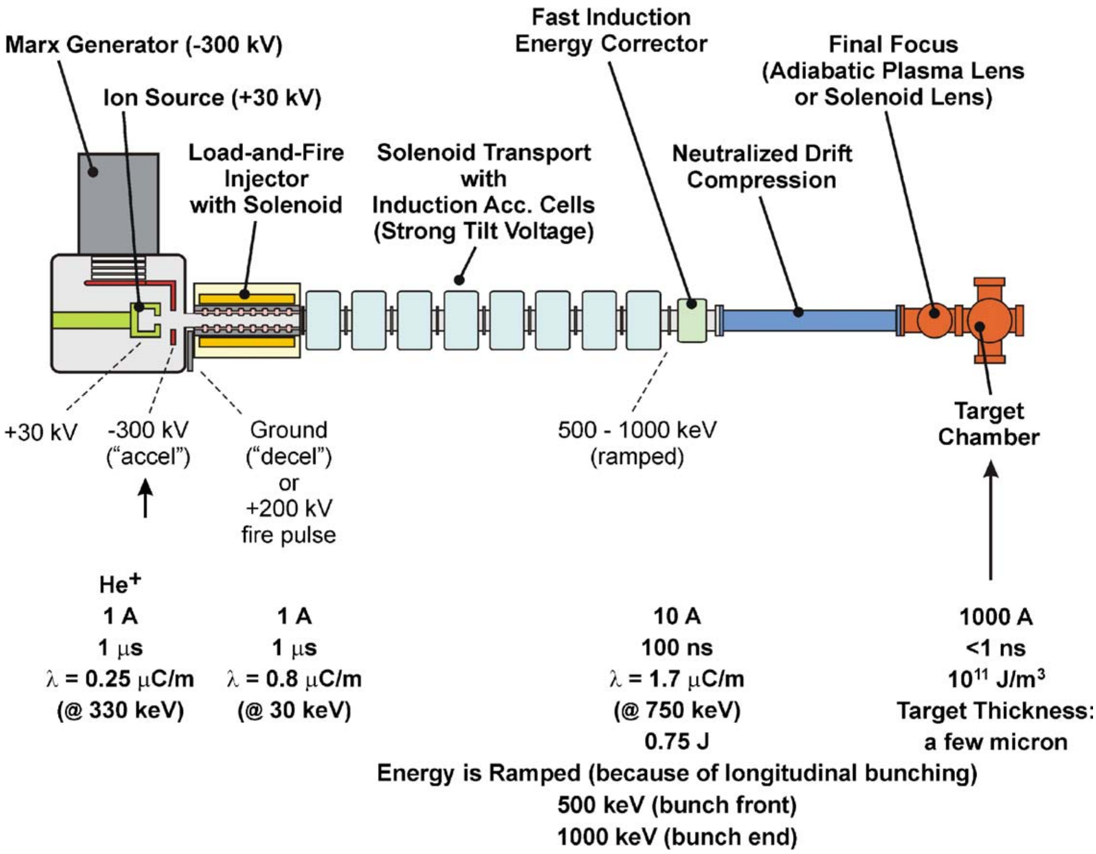

Fig. 4. Schematic concept of the Neutralized Drift Compression Experiment (NDCX-II).

This beam pulse is subsequently injected into the neutralized drift compression section. An approximately $10^{12}\,\mathrm{cm}^{-3}$ dense background plasma (10 times the beam density) provides space-charge neutralization for the ion beam. After longitudinal compression by a factor of >100 to less than 1 ns pulse length, the now ~1 kA ion beam is focused on target by a final focus lens, which could either be an adiabatic plasma lens or a strong focusing solenoid. The final focal spot is less than 1 mm diameter, leading to $>10^{11}\,\mathrm{J/m^3}$ energy density in a 1 μm thick target foil.

NDCX requires novel beam manipulations, the load-and-fire injector, the neutralized drift compression section, and the final focus system. In addition, the high space-charge beam of NDCX necessitates solenoid focusing instead of quadrupole focusing as in IBX. To validate these essential components experimentally, NDCX will be built in two phases.

Phase 1, or NDCX-I, extends the existing Neutralized Transport Experiment (NTX) hardware [1] as shown in Fig. 5: two beamlines in parallel will test either the neutralized drift compression (beamline "a" in Fig. 5) or the load-and-fire and solenoid transport concept (beamline "b" in Fig. 5).

Four existing quadrupole magnets at the first beamline will be used to match the 25 mA, 300 keV NTX beam into a short neutralized drift compression section to be built in FY 2005. An existing induction cell, fabricated by First Point Scientific, will apply the required tilt voltage to compress a small section of the 1 μs NTX beam by a factor of 10.

As a second independent experiment, a solenoid transport line will be built, including a prototype 100 kV load-and-fire injector (i.e. with a 100 kV "fire" pulse). NDCX-I experiments will not have induction cores for beam acceleration.

NDCX-I will measure the parallel and transverse temperature of a high perveance ion beam before and after longitudinal compression by a factor of ten in neutralizing background plasma, and before and after pre-bunching of a nonneutral beam in an acceleration–deceleration configuration. This series of experiments and modeling is required to plan and design the second phase of NDCX (as shown in Fig. 4), which will now incorporate a 200 kV load-and-fire injector, acceleration cores, and a 100× neutralized drift compression.

NDCX-II will compare the measured and simulated focal spot beam intensity profiles in integrated experiments with beam current and energy sufficient to provide $10^{11}\,\mathrm{J/m^3}$ (the high-energy-density threshold level) in targets. This series of experiments and modeling of compression and focusing will provide the physics basis for a future heavy-ion high-energy-density-physics facility (NDCX-III) as shown in Fig. 6.

3.3. NDCX cost & schedule

Fig. 7 shows the proposed HIF–VNL program plan to develop the Neutralized Drift Compression Experiment in a 5-year time frame. NDCX-I will primarily use existing equipment to develop a neutralized 10-times drift compression and a 100 kV load-and-fire injector until FY2006. In the second phase, NDCX-II will integrate a 100-times drift compression and a 200 kV load-and-fire injector together with induction acceleration cells using solenoid transport magnets. The estimated cost for NDCX-II is ~4 FY04-M$ until FY2009. Based on the experiences gained with NDCX-I and NDCX-II a future heavy-ion-beam-based high-energy-density-physics user facility will be proposed which could be operational by FY2015 at an estimated cost of approximately 50 FY04-M$.

4. Summary

An integrated beam physics experiment for the heavy-ion fusion program in the US is considered of "highest scientific priority" [11] in the 20-year strategic plan of the US Department of Energy Office of Science. The HIF–VNL has developed two rather different project proposals to further integrate heavy-ion beam science relevant to inertial fusion energy and high-energy-density-physics research, the Integrated Beam Experiment (IBX) and the Neutralized Drift Compression Experiment (NDCX). The well-developed IBX, which focuses on the scientific exploration of the

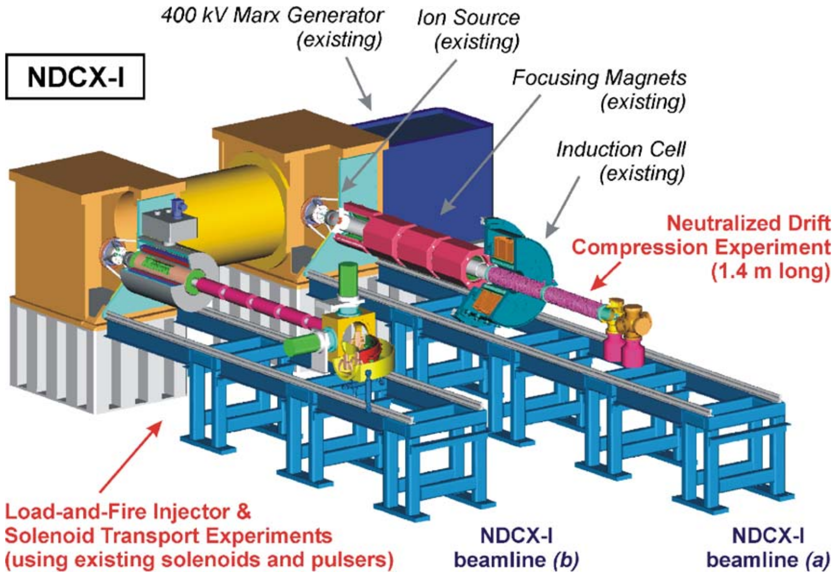

Fig. 5. NDCX-I (phase 1) will extend the existing NTX hardware with two independent beamlines: A neutralized drift compression experiment on beamline (a) and a solenoid transport experiment with a prototype load-and-fire injector on beamline (b).

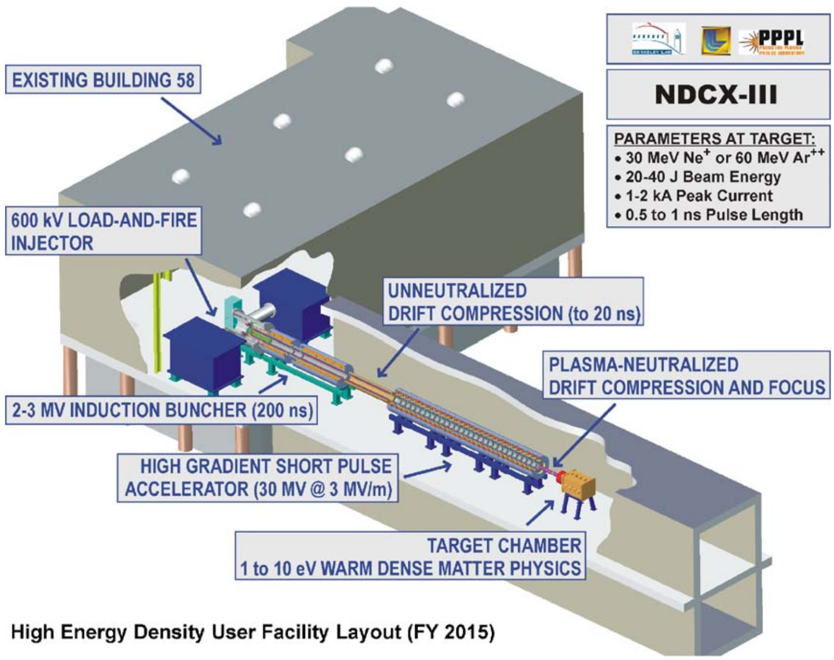

Fig. 6. Schematic layout of NDCX-III, a proposed high-energy-density user facility based on transport, acceleration, and compression techniques developed in an integrated manner in the Neutralized Drift Compression Experiment (NDCX).

ion beam evolution over a large number of transport lattice periods, could be built immediately. The much smaller, and more specialized NDCX, requires novel ion beam manipulations which can be developed over the next 5 years in a cost-effective manner. NDCX would push beam

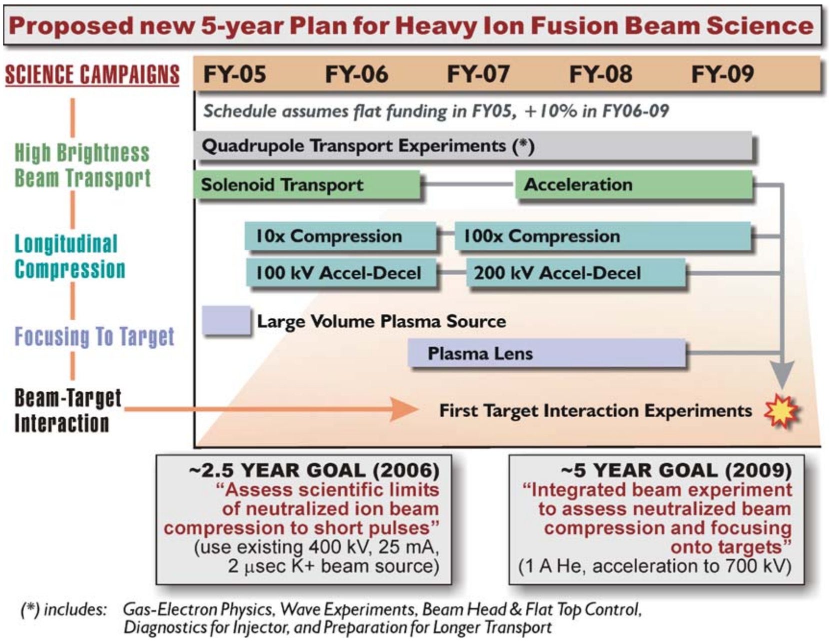

Fig. 7. HIF–VNL program plan developing the Neutralized Drift Compression Experiment (NDCX) in a 5-year time frame.

compression to the limits, therefore providing significant beam pulse energy on target for high-energy-density-physics experiments, even for the near-term experiments.

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